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Lighting Spectral Effect on Landolt C Performance is Enhanced by Blur and Abolished by Mydriasis

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Abstract

When pupil size is changed by varying the surround spectrum, there is a perceived color shift of the task towards the complementary hue of the surround. This occurs even though none of the surround light falls on the task, and the task illumination is unchanged. This induced color effect is a neural process. To investigate whether such a mechanism is an alternative explanation of our results on the effects on visual performance of spectrally controlled pupil sizes, we studied visual performance both with and without mydriasis (pharmacologically dilated and fixed pupil). If the induced color hypothesis is valid, then it should occur with both fixed and light-responsive pupils. In addition, we studied whether the pupil size effect on visual performance can occur in accurately refracted subjects, or if it is enhanced by the addition of a small amount of optical blur (+0.50 DS). We studied 12 subjects, 21 to 35 years of age, correctly refracted and with added blur, under each of two conditions: normal pupils and mydriasis. We compared Landolt C recognition, with a fixed task luminance but variable contrast, for two different surround spectra, each at 50 cd/m^2. The two different surround spectra controlled subject's pupil size. For normal pupils, performance was better with smaller pupils, and the improvement in performance due to switching to a scotopically enhanced surround was greater with added blur, even though blur reduced overall performance. Under mydriasis, change of the surround spectrum had no effect on performance, whether there was blur or not. However, the added blur reduced performance under the mydriasis condition, showing our measures are sensitive to these parameters. These experiments rule out the induced color hypothesis and demonstrate the benefits of smaller pupils on Landolt C contrast sensitivity even when subjects are correctly refracted. Further, the results indicate that the measured improvement due to pupil size change is greater when there is imperfect refraction (blur).

Introduction

In our previous studies[1,2] relating visual performance and pupil size changes, we have independently varied surround luminance and task luminance. Pupil size of test subjects has also been controlled by changing the surround spectrum. A scotopically enhanced surround spectrum elicits significantly smaller pupils than a scotopically deficient spectrum, both at the same photopic luminance. Performance on Landolt C recognition and word reading accuracy at fixed task luminance has been shown to be significantly higher when the surround lighting is scotopically enhanced, yielding smaller pupils. Under these comparisons, the perceived color of the surround illuminations are quite different, causing the perceived color of the foveal task to change when the surround illuminant is changed. This perceived effect is not due to any surround light leakage onto the task, but is the result of the neural process of chromatic induction.[3] Chromatic induction describes the process whereby the color of the surround induces the complementary color in the central portion of the visual field, i.e., in the whitish immediate task background surrounding the Landolt C in our experiments.

Since we did not control for this effect in our previous studies, chromatic induction could be an alternative hypothesis for the performance effects we observed. Under this hypothesis, visual performance is better when the task background has an induced pinkish hue (the color induced by the scotopically enhanced surround spectrum illuminant) and is poorer when the induced background color is greenish in hue (the color induced by the scotopically deficient surround illuminant).

To test this hypothesis, we compared subject performance in two conditions: natural pupils and fixed, dilated pupils. If chromatic induction is the dominant mechanism, then performance should be similar under both natural and mydriasis conditions. On the other hand, if the pupil size variation is the dominant mechanism, then the performance differences observed with natural pupils should be absent for the same subjects under mydriasis where the pupil is stationary. For such a comparison to be valid, subjects must be refracted under both conditions to account for accommodative effects of the mydriatic.

Because we refracted our subjects in this study, we were also able to test whether spectrally induced pupil size changes cause greater or less improvement in visual performance when subjects perform the task correctly refracted, as compared with the addition of a blur lens. In our previous studies we did not control for subject refractive state other than require that subjects possess a minimum of 20/30 vision. Since it has been demonstrated that pupil size effects on vision are more pronounced under conditions of increased dioptric blur,[4] the question arises as to whether our previously observed performance differences were mainly a result of the relatively uncontrolled refractive state of subjects.

The study presented here shows that induced color is not the mechanism underlying the performance changes, and further demonstrates that correctly refracted subjects perform better with smaller pupils than with larger pupils, this effect being greater with added refractive error.

Methods

Subjects

Three female and eleven male students between the ages of 21 and 35 were recruited from the University of California at Berkeley, School of Optometry. All subjects, after giving an informed consent approved by an independent review board, were examined during a screening visit by an optometrist (Author MAB). Each subject's distance optical correction (refractive error) was determined for each eye, with both natural and dilated pupils using standard optometric techniques[5]. Measurements were made first for natural pupils at a test distance of six meters. Following this, one drop of 1% tropicamide hydrochloride (Mydriacyl, Alcon Labs) was instilled into each eye. Tropicamide is an anti-muscarinic which relaxes the sphincter pupillae muscle, thus producing a dilated pupil,[6] abolishing the pupillary light reflex, and paralyzing accommodation (the ability to change focus for near work). Fifteen minutes after the drug instillation, the refractive error was again determined. In a few subjects there was a small difference in refractive error between the natural and dilated pupils. This could be due either to the relaxation of accommodation or an increase in spherical aberration associated with a larger pupil[5].

The optical corrections thus obtained were later used during the visual performance testing. That testing took place in two separate sessions, usually on separate days. For testing under mydriasis, two drops of tropicamide were instilled in each eye. We then waited 20 minutes after administration before beginning the experiment. Subsequently at 1.5 hour intervals one drop was administered in each eye until the procedures were completed. Only one subject had more than three drops put in each eye.

Pupil Size Recording

An ASL Model 4250R Eyetracker/Pupillometer was used to measure subjects' pupil size continuously as they performed the task. The instrument measures pupil diameter (horizontally across the pupil), at a sampling rate of 60 Hz. The ASL PC-EYENAL (V. 2.1) software package was used to remove blink artifacts.

Blur Condition

For all testing, the subjects viewed the task through glasses. These glasses either provided a full correction, or a full correction plus a small positive blur, typically 0.50 DS. For one subject it was slightly lower (0.25 DS) and for another subject slightly higher (0.75 DS) in order to achieve significant performance changes within the contrast variations available.

Surround Lighting

The study took place in a light tight rectangular room of dimensions 2m x 2m, with ceiling height of 2.5m. The walls and ceiling were painted with a high reflectance, spectrally flat, white paint (Kodak). Surround lighting was provided indirectly by fluorescent lamps of two different spectra, a scotopically enhanced lamp (F213) with a greenish-blue hue which has its spectrum peaked at about 510 nm, and a scotopically deficient lamp, pinkish in hue.

These lamps were chosen to have a large color difference, to maximize differences in induced colors. The ratio of scotopic to photopic luminance for the lamps were S/P = 4.31 for the F213 and S/P = 0.54 for the pink lamp. The lamp fixture was located directly above, but shielded from the subject's head, 1.4m from the front viewing wall and extended down 0.5m from the ceiling (Fig. 1). The wall luminance was measured with a Pritchard Spectrophotometer (Model 1980A), at a point on the front viewing wall approximately 1m from the floor and 0.5m from the left wall. The luminance distributions were approximately constant and similar for the two lamps. For the study, the front wall photopic luminance was set at 50 cd/m^2 for both lamps.

Task

The task used for this study, a Landolt C presented on a video-display terminal (VDT), is the same as used in our previous studies.[1,2] The C subtends a visual angle of approximately 15 minutes with a gap of three minutes of visual angle. The task is viewed at a distance of 3m, achieved by a front surface mirror situated at a distance 1.5m directly in front of the subject chair (Fig. 1). The immediate task background was set at a luminance of 13.2 cd/m^2 and the C contrast was varied by changing the luminance of the C. Surrounding the C were four black bars (> 90% contrast), arranged in a cross-hair fashion, which were continuously present on the background. These bars gave the subject something upon which to fixate between presentations of the C, and also provided an accommodative cue.

Contrast was determined using the Pritchard Spectrophotometer to obtain a mean luminance of the C (L_T) by averaging the values measured at 12 different points on the C surface, and a mean luminance of the task background (L_B) by averaging the luminance at five points around the C. The contrasts used for the study were in logarithmic steps taking the values 4, 6, 10, 16, 25, 40, 63 and 80%, with contrast defined as the ratio (L_B-L_T)/LB. A matte black shield covered most of the VDT surface except for a diamond shaped opening approximately five times larger than the C. This shield extended an additional 0.9m from the front of the VDT to eliminate direct reflections of the surround lighting onto the VDT screen. The viewed front surface mirror was surrounded by a matte black cloth (Fig. 1) which provided a black surface subtending a visual angle of 20 degrees with the central opening of the VDT shield subtending slightly larger than one degree. The C luminance on the VDT was produced with a Matrox graphics card. The C's were oriented to face the four diagonal directions (NE, NW, SE, SW, with north defined as the ceiling) by tilting the VDT 45 degrees. This was routinely done in our experiments in order to avoid any interaction between possible slight differences in the C on the VDT (horizontal or vertical), with any astigmatic differences (which are commonly near horizontal). Such potential effects were minimized in the present experiments because any astigmatism was corrected (within 0.25 diopter).

Testing Procedure

Subjects were seated in a comfortable chair in the experimental chamber and familiarized with the various equipment. The pupillometer focus and eyetrack positioning were then adjusted and calibrated. At the outset of the experiment, each subject was given a several preliminary sets of Landolt C presentations under the pink lamps. After the subject was familiarized with the procedure, these preliminary trials were continued to determine which four contrast values lie closest to the ascending portion of their probability of seeing curve. After each trial set, the subjects scores were evaluated by the experimenter. If the subject scored perfectly on the highest contrast, the range was lowered. Similarly, if the subject scored at total chance on the lowest contrast, the range was raised. Within the contrast constraints described above, it was not always possible to find a range where the subject scored neither at total chance nor perfectly for all contrasts. No subject had floor or ceiling effects for more than one contrast. This method of determining the best contrast range was repeated four times: once with clear lenses and once with blurred lenses, under both mydriasis and natural pupils.

Before each set, the subject was given a minimum of two minutes to adapt to the change in surround lighting condition. Each C was presented for 200 msec, and the subject was given as much time as needed to make her forced choice by pressing one of four buttons corresponding to the possible C orientations. Sets lasted approximately five minutes, during which pupil size was continuous recorded. Between sets the subject could choose as much time as desired to relax.

Task Sequence

Four conditions (Corrected or Blurred, under F213 or Pink) were tested in two sessions: once with natural pupils and once under mydriasis. It was randomly determined for each subject whether the natural or mydriasis session came first. Test sessions were on different days except for seven subjects, who completed the natural and dilated sessions in one day, in that order. For each condition, a subject was presented four C contrast levels (as determined by the method described above) with 60 presentations for each contrast (a grand total of 240 presentations per condition). To minimize subject fatigue, each of the four conditions were broken up into three sets. Each set consisted of 20 presentations of each of the four contrast levels (a total of 80 presentations) presented in random order. Within each session, the resulting 12 sets were presented in random order.

Data Analysis

For each subject, pupil area was averaged across the three sets of each condition. The SAS GLM procedure was used to analyze these averages using a 2x2 (blur by surround light) balanced repeated measures ANOVA for the natural and mydriasis conditions separately.

The performance data were analyzed in two ways: using structured covariance matrices to perform polynomial modeling of the data, and modeling the data as probability of seeing functions using Probit function Logistic Regression. We chose to use the polynomial modeling as our primary analysis for two reasons. First, polynomial regression is likely to be a more sensitive measure of the effects of surround lighting and blur because it focuses on modeling the ascending portion of the performance curve where those effects are most apparent. Second, most probability of seeing modeling assumes a symmetric probability of seeing curve, which may not be valid because of a possible shift in criterion at lower contrasts where the task becomes more difficult. Visual inspection of the performance curves suggests that such may be the case. Moreover, with only four contrasts studied per subject per condition, enough data were not available to accurately model performance with an asymmetric probability of seeing model. Thus, the primary analyses used polynomial modeling, with the probability of seeing analysis performed to also express effect sizes in traditional probability of seeing terms.

The primary analysis used the 5 V procedure of the BMDP statistical package[7] to analyze the performance data within a 2 x 2 x 4 repeated measures Analysis of Variance framework, separately for the normal pupil and the mydriasis condition. The factors were: Blur (corrected vs. blur), Surround lighting (50 cd/m^2 F213 vs. 50 cd/m^2 pink), and Contrast (four levels). Since the range of task contrasts was different for different subjects and sometimes needed to be adjusted within a subject between conditions (to accommodate for poorer performance with blur and/or dilation), the data were unbalanced and could not be analyzed using standard ANOVA procedures. The 5 V procedure uses Maximum Likelihood estimation with structured covariance matrices to solve the unbalanced design problem. Prior to statistical analysis, for each subject, the Landolt C task accuracy (i.e., percent correct) was computed for each of the four contrast levels, for each of the eight experimental conditions. Task-contrast was converted to effective task contrast by adjusting for the effective ocular veil luminance produced by surround light scattered in the eye (approximately 4% of surround luminance for the geometry of our study), and by the small amount of light traversing the tube (1%). In BMDP-5V, the unbalanced factor [$\log_{10}$ (effective-task-contrast)] was analyzed as a covariate, which varied across the repeated measures. Both linear and quadratic effective task contrast effects on Landolt C accuracy were estimated.

The probability of seeing analysis was performed using the SAS Logistic Procedure with the Probit function[8]. Data for each subject under each experimental condition (mydriasis by blur by surround light) were analyzed separately as performance vs. $\log_{10}$ (effective task contrast), yielding estimates of the best fit slope and inflection point for the probit curve. The SAS GLM procedure was then used to analyze the slopes and inflection points as dependent variables within 2x2 (blur by surround light) balanced repeated measures ANOVAs separately for the normal pupil and mydriasis conditions.

Results

The pupil area data are presented in Figure 2, while the Landolt C performance data are presented in Figure 3. Note that, even though each subject was only studied under four contrasts, the Landolt C performance data are plotted for six or seven values of effective task contrast. This reflects the fact that different contrasts were used for different subjects and across different conditions. The area of the circles in Figure 3 is proportional to the number of subjects who contributed to the measurement at each point.

Dilated Pupils

The mydriasis was effective. Under mydriasis, all subjects had dilated pupils ranging from 36.0 to 59.3mm^2 with a mean of 46.6mm^2 (2.3 mm^2 s.e.). There was a very small change in pupil size as a function of surround spectrum with a mean reduction of 3.8% under the F213 surround condition ($F1,11 = 25.1$; $p = 0.0004$) indicating that the mydriasis, although effective, was not total. With such dilated (and essentially fixed) pupils, there was a highly significant linear effect of $\log_{10}$ effective-task-contrast on Landolt C accuracy [χ^2 (1 df) = 30.61, $p< 0.0001$] and a highly significant reduction of 26.0% (s.e. 1.7%) in Landolt C accuracy with the blurring lens [χ^2 (1 df) = 245.3, $p < 0.00001$]. With dilated pupils, there was no effect of spectrum of the surround lighting on Landolt C accuracy [χ^2 (1 df)= 2.19, $p = 0.14$]. The p=0.14 value should not be interpreted as a trend for a surround effect, since the means were in the direction of slightly better performance (+2.3%, s.e. 1.5 %) for the scotopically deficient surround lighting, a direction opposite to that observed with light-responsive pupils.

Normal (i.e., light responsive) pupils

With normal pupils, there was a strong effect of surround spectrum on pupil size. Pupils were reduced by about 41.8% (s.e. 2.7%) from a mean value of 21.5mm^2 (s.e. 2.2mm^2) for the pink lamp to 12.2mm^2 (s.e. 1.1mm^2) under the F213 lamp. With natural pupils, there were highly significant linear and quadratic effects of $\log_{10}$ effective task contrast on Landolt C accuracy [χ^2 (1 df) = 92.9 and 8.9, $p << 0.00001$ and $p=0.003$, respectively], and a highly significant reduction of 27.1% (s.e. 1.4%) in Landolt C accuracy with the blurring lens [χ^2 (1 df) = 372.6, $p \leq 0.00001$]. With light responsive pupils, there was a main effect for the surround illuminant [χ^2 (1 df) = 80.6, $p <<0.00001$], wherein performance was 12.0% (s.e. 1.3%) better on average for the scotopically rich illuminant compared to the scotopically deficient illuminant. There was also a significant interaction effect ($p = 0.029$) wherein the improvement with scotopically rich lighting was larger under the blur condition (14.8% s.e. 1.8%) than under the non-blur condition (9.0% s.e. 1.7%).

Probability of seeing results

The pattern of statistical results from the probability of seeing analysis was very similar to that reported above, although the significance levels were somewhat lower. The shift in the probability of seeing curve with blur was 0.25 (s.e. 0.07) and 0.24 (s.e. 0.10) $\log_{10}$ effective-task-contrast units for natural and dilated pupils, respectively. For the natural pupil condition, the shift in the probability of seeing curve with scotopically rich surround lighting was 0.16 (s.e. 0.11) and 0.10 (s.e. 0.09) log10 effective-task-contrast units for the -blur and non-blur conditions, respectively (see Table 1 below for a summary of these effects). For this analysis, the surround light by blur interaction effect was only a weak statistical trend ($p = 0.19$). For the dilated pupil, the shifts for scotopically rich lighting were non-significant for both the blur and non-blur conditions [-0.05 (s.e. 0.07) and -0.02 (s.e. 0.11) $\log_{10}$ effective-task-contrast units, respectively].

A summary of the various effects and their significance levels for the probability of seeing analysis is provided in Table 1.

Discussion

The results of our study support three principal conclusions. The first conclusion is that the visual performance effects caused by a scotopically-enhanced surround are not due to any hypothesized induced-color effect. In the mydriasis condition we found no differences in Landolt C visual performance when the surround lighting was changed from scotopically enhanced (F213 lamp) to scotopically deficient (pink lamp), while maintaining the same photopic luminance, even though the task color shifted towards the complementary hue (greenish for the pink lamp and pinkish for the F213 lamp). Thus we conclude that the induced color difference of the task, caused by the different surround spectra, is not the mechanism responsible for the performance effects observed in the same subjects with normal, responsive pupils, i.e., better performance on the Landolt C task with smaller pupils.

Our second conclusion is that the pupil size effect on performance occurs even when subjects are correctly refracted. The observation that subjects performed better on the Landolt C task under the scotopically enhanced surround light indicates that these results generalize to the whole population, whether they have *perfect* eyesight or not. Note that *perfect* here means within the limits of the optometric examination we used.

Our third conclusion is that those with some imperfections in their eyesight (at least those similar to our blur condition) will benefit from smaller pupils even more than those with *perfect* eyesight. The surround condition with scotopically enhanced lighting that produced smaller pupils for the natural pupil condition had a greater performance increment with the added blur than occurred under the scotopically deficient surround lighting (with larger pupils). These results confirm those of Atchison et.al.[4] extending this relationship to natural pupils with binocular viewing (rather than the artificial pupils and monocular viewing used by Atchison), to the small amounts of blur that are common in the population, and to surround lighting levels in the range of those encountered in interior lighting. Thus, our results extend those of Atchison et. al.[4] to a situation that should be more appropriate for lighting practice.

Since the task was situated about 3m distance from the subject position, the change of blur power (0.50 DS) should assure that accommodation did not play a role in the subjects' performance. On the other hand, because we did not undertake to experimentally verify exactly where our subjects fixated between trials, e.g., they could have inadvertently shifted their fixation from the task to the mirror edge, the black curtain, the tube edge, etc., we cannot unequivocally argue that the improved performance is solely due to improved acuity under the smaller pupil conditions. Since the task presentation duration was 200 msec, it is possible that the subjects were accommodating for a different distance at the time of task presentation and the performance differences obtained were related to the larger depth of field occurring with the smaller pupil. In our study of word reading accuracy,[9] the task arrangement was much simpler and there was an absence of other visual material located at different distances, thus assuring steady accommodation. In that study, subjects performed better with smaller pupils, which supports our hypothesis of a primary pupil size effect on Landolt C recognition

Fig. 2 shows a small, but statistically-significant, increase in natural pupil size in the blurred condition ($p = 0.01$). We corrected the calibration of the pupillometer for the change in the magnification of pupil size due to the +0.5 DS lens. The change in pupil size may be due to a sympathetic reaction to the more difficult task, or due to changes in the threshold adjustment of the pupillometer that we did not control for. We are unable to distinguish between these and other possible causes.

This study, along with our five other studies[1,2] (each carried out with a different set of subjects ranging in age from 20 to 70 years old), represent a collection of demonstrations of the effect of spectrally controlled pupil size on visual task recognition or discrimination. In all of these studies, task performance was compared at two different pupil sizes obtained by changing the surround lighting conditions while task luminance was held fixed. The results of each comparison showed that performance was significantly better when pupils were smaller. In these studies, pupil diameters ranged on average from 3.5 mm to 4.8 mm, while task luminance varied between 12 cd/m^2 and 80 cd/m^2. Because task luminance was held fixed while pupil size was manipulated through the surround variations, the results all demonstrate that recognition or discrimination is improved under the condition of lower task retinal illuminance (i.e., the smaller pupil condition).

This result leads us to hypothesize that when task luminance is in the photopic region, improvements in visual recognition or discrimination ostensibly arising from increasing illumination levels must in part be a result of decreasing pupil size, rather than solely due to increased retinal illuminance. This hypothesis is also supported by various other studies in the vision literature[10,11] which show grating acuity and contrast sensitivity to asymptote at low photopic values of task luminance for conditions of fixed pupils.

If pupil size is an important factor controlling visual recognition and discrimination at photopic light levels, then the lighting community has a significant opportunity to improve the national lighting energy efficiency while maintaining present standards of visual performance. Thus a solution is to shift lamp spectra toward scotopic enhancement while operating lighting at lower energy levels.

Acknowledgment

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Discussions

I must admit that I really don't understand the point of this paper. The authors' hypothesis that the color of the surround might account for the results of their previous papers isn't at all explained. Did someone suggest that chromatic induction is a plausible explanation for acuity differences? If so, the criticism should be referenced (it is not). If someone did not suggest such an explanation, why did the authors design this experiment to disprove it? Did they think that it is a plausible argument? If so, they should make that argument. Otherwise, this paper comes across as a "straw man" experiment. I'm sure such is not the case and the paper would be significantly strengthened if the reason for it were better justified.

My only other question has to do with the refraction distances. The authors stated that Dr. Bullimore refracted the subjects at 6 meters; however the experimental data were taken at 3 meters, leaving a residual refractive error of approximately 0.33 diopters which, as Atchison et al have shown, might cause a pupil size dependent effect secondary to blur. Why were the subjects not refracted at the testing distance? Also, in this age group, one drop of tropicamide rarely causes significant cycloplegia (paralysis of accommodation). Placing +0.50 in front of these subjects may have simply brought them back to near conjugate focus, although the reduction in performance with that lens would seem to indicate that blur was induced (which is surprising since they were 0.33 diopters hyperopic at 3 meters -- assuming cycloplegia).

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The authors tested an interesting hypothesis on the nature of the colour shift phenomenon. The multidisciplinary approach, involving lighting, behavioural and ophthalmic research communities is a commendable example to be followed.

The authors presented evidence for rejecting their null hypothesis that the effect is caused by chromatic adaptation to entoptically-scattered light. They do not, however, directly test their alternative hypothesis that the effect is due to spectrally-controlled pupil sizes. Cycloplegics affect not only pupil size but all functions of the near reflex.

The null hypothesis is nonpharmaceutically testable using artificial pupils or by studying the effect as a function of age-dependent entopic scatter. Might the authors have age-related data to further support their conclusions?

The results depend upon presentation of stimuli at matched levels of luminance. The stimuli involved luminous surrounds with different spectral content - an appreciable challenge for a photometer having imperfect spectral correction and highly scatter-prone optics. Were the photometric measurements verified by spectroradiometry and more appropriate instruments?

We consistently observed that contrast has a greater effect on visual performance when the vision is degraded by decreased luminance or size. Likewise, contrast should have a greater effect when vision is degraded by blur. The slopes of the curves in Figure 3 appear unaffected by blur, however. Could the authors explain this?

The authors call their dependent measure visual performance, yet they didn't isolate the visual component of the response from cognitive and motor components. It's more appropriately called task performance.

They suggest that pupil size - and supposedly not luminance, contrast or stimulus size - is the controlling factor for photopic vision. This untested hypothesis runs counter to stimulus-response functions from all disciplines in sensory psychophysics. When pricking one's finger, or uttering a sound, or view an object, the stronger the stimulus the greater the sensation and the more pronounced the response. We found that visual processing time improves with increasing luminance, size, and contrast, even when viewing through fixed constricted artificial pupils. Visual performance derived from detection tasks agreed with that from numerical verification. Our results therefor do not support the authors suggestion.

Minuscule stimuli, special paint, and pink lights were used to demonstrate a small effect which the authors consider generally exploitable. The paper does not demonstrate the utility of the effect for less contrived conditions usually found in buildings.

Mike Ouellette
National Research Council
Institute for Research in Construction

Authors' response

To A.L. Lewis

The induced-color hypothesis was suggested by us as an alternative hypothesis in the Discussion section of our previous Landolt C performance paper, (see reference 1 of this paper). Thus, we designed an experiment that could rule-out this induced-color hypothesis. The same experiment could also demonstrate that visual effects shown here, and in previous studies, were due to pupil size changes, by showing (as they did) that the visual performance effects of changing the spectrum of the surround disappeared with a fixed pupil.

However, since the mydriatic needed to fix pupil size also affects accommodation, the experiment required that both visual performance tests be done under the same refractive state, thus requiring correct refractions. Before the experiments we were uncertain as to whether an effect would be observed when subjects were correctly refracted. This uncertainty arose because: 1) a perfect lens system would not show an effect of aperature size on image resolution, 2) in our previous studies, an occasional subject would not show the effects seen in most subjects (leading to a question as to whether they had perfect vision), and 3) we had not, in previous studies, recorded the refractive state of subjects (leaving the possibility that effects might be due to uncorrected optometric errors). Thus, we designed the experiment with the blurred condition in case there was no effect in the corrected case. Since there was an effect in the corrected case, we were thus able to compare the size of the effects when corrected and when blurred. This is the genesis of the experimental design. We hope that this description, along with considerable revisions to the Discussion section (which Dr. Lewis did not see) clarifies the point of the paper.

Although induced color is a well known phenomena in vision science, we could find no studies in the literature of possible effects of induced color on visual performance. In the absence of such information, we have followed one of the traditions of scientific research and have investigated whether the proposed induced-color hypothesis could account for our observations. Without such an investigation, that alternative cannot be ruled out and we would have failed to demonstrate unequivocally that the underlying mechanism is pupil size changes.

We chose to refract for the 6m distance because that is the standard condition used in optometric examinations and using such a correction in our experiment correctly mimics the situation in which a subject is wearing a correct eyeglass prescription. Since our task was placed at 3m, the possible refractive error is 1/6 D, not 1/3 D as Dr. Lewis states. Hence the +0.50 DS lens does not bring the subject to near conjugate focus. This residual 1/6 D of possible refractive error is well within what is considered the accuracy of clinical refraction (which is about 0.25 D).

Although only one drop of tropicamide was used for subjects when they were refracted, the text has been revised to correctly describe that two drops were used at the time they participated in the study, with supplementation each 1.5 hours. A small difference in accommodative paralysis, say between 90% and 100%, would not be expected to affect our results where the task is at 3m. Dr. Lewis's comment regarding a pupil size effect secondary to blur is particularly apt since we did also observe such a change in the normal pupils; we have modified our figures and text to include this data (not included previously).

To M. Ouellette:

We do not understand the hypothesis that the effect shown in this paper could be explained by the effects of the cycloplegic on the near reflex. We first demonstrated that the improvement in visual performance due to a scotopically-enhanced surround occurred on our subjects under natural pupil conditions (no mydriatic). We then found that, in the same subjects, performance was not affected by surround spectrum under the conditions of fixed pupil under mydriasis. We do not feel that the action of the near reflex under natural pupils could explain the observed performance change, and hence its paralysis should not have significant consequence. Without further hypotheses, we consider that the mechanism of pupil size in the performance change has been demonstrated. We do not agree that the null hypothesis is nonpharmaceutically testable using artificial pupils. With an artificial pupil there would not be any color induced for the surround (since the artificial pupil blocks vision of the surround). Further, an experiment with an artificial pupil cannot show that the visual performance benefit of changing the surround spectrum disappears when the pupil size is fixed, since the surround has no effect with an artificial pupil.

Regarding age-dependent effects, Berman et al. (1994)[2] is a study showing that performance changes in elderly subjects (age 60-70) are comparable to performance changes in young adults (age 20-40) even though pupil size changes were considerably less in the elderly subjects.

The concerns raised about photometrics are not relevant to our study as the task conditions do not change when the surround lighting changes. The results do not depend on the equality of surround luminances for the two different surround illuminants, the results require only that the two different surround illuminants produce different pupil sizes, as they indeed do. We have previously discussed the spectroradiometry used in our studies[a] and believe our instrumentation is appropriate.

The statement made that the slope of visual performance vs. contrast curves changes with task luminance and size most likely refers to Rea and Ouellette's reaction time study[b]. For that study the task was a detection task (using monocular vision) of a square whose size, luminance, and contrast was varied. The task in our study involves a resolution task, rather than a detection task, and the Landolt C gap opening was viewed with and without a blurring lens. We do not see why fundamentally different visual tasks, viewed under different experimental conditions, should necessarily have a similar slope behavior.

Our data shows a significant shift towards higher threshold contrast for the blur condition. This is what is expected by the classical probability-of-seeing analysis used in vision science to analyze visual performance, rather than a change in the slopes. We agree with Dr. Ouellette that our experimental procedure does have non-visual components, but in comparing the difference under the two surround lighting conditions, it seems highly unlikely that the role of non-visual components are significant.

In some ways, this research may appear to contradict some principles of sensory psychophysics, but upon a closer inspection there is no contradiction. In our previous studies there are two factors that are changing under the protocols used: pupil size and task luminance (see paper presented here on Word Reading Accuracy). If pupil size is fixed i.e., the optical operating conditions are specified, then increasing task luminance will provide an increase in performance behavior. However, if pupil size is changed while task luminance is fixed, then task retinal illuminance does change, but the resultant change in performance cannot be predicted on general principles, because the optical operating condition is now different. An imperfect optical system will not necessarily focus the added light rays admitted by a larger pupil at the same focal area as the paraxial rays, thus decreasing optical quality even though there is more overall illumination.

Since the reaction time study (the detection task referred to by Ouellette) used fixed artificial pupils, and since pupil size was not measured in the numerical verification study, it is unclear how those studies relate to our results. However, in a different study by Rea and Ouellette[c] pupil size was measured, and it has been pointed out in the discussion section of reference 1 that their data shows a clear pupil size effect consistent with our hypothesis. We have not stated in our papers that pupil size alone "is the controlling factor for photopic vision." We have stated that changes in pupil size can have an effect on task performance, despite changes in retinal illumination.

The relevance of contrived conditions in studies demonstrating a small effect with minuscule stimuli has been questioned in our work. We believe that for a result to be generally exploitable, performance on a visual task should be objective when comparing spectrally different lighting systems. Consider the method used in eye examinations for deciding on the correct refraction. The optometrist does not ask if the large letter E is clear, but test small letters in order to have an objective criterion of visual acuity. Even if there are no letters ever to be seen that are as small as the test letters, wearers of spectacles will see larger letters with cleaner edges when they are viewed with the correct refraction. The same spectacle wearers will complain of visual problems if they are using spectacles with incorrect refractions. This is because objects and letters have edges and corners whose visual sharpness depends on higher spatial frequencies.

However, the purpose of this study was to rule out specific scientific hypotheses (see our reply to Dr. Lewis), and hence we used special paint and unusual lamps. That is, we did not, nor do we, expect that these specific results should be directly extrapolated to a workplace environment. By choosing lamps with markedly different spectra, we maximized the differences in induced color, and thus maximized the likelihood of finding an effect, if the effect existed. Not finding the effect under these extreme conditions means that it is not reasonable to consider that an effect can occur under conditions having even less induced color.

On the other hand, our collection of studies showing the effects of scotopic sensitivity on visual performance and brightness perception implies that lighting practice based on conventional photometry alone will be inadequate.

References

(a) Berman S.M. et.al. 1992. Spectral Determinants of Steady State Pupil Size with Full Field of View, *J. of the IES*, 21(no.2)

(b) Rea, M.S. and Ouellette, M. 1990. Visual Performance Using Reaction Times, *J. of the IES*, 19(no. 2).

(c) Rea, M.S., Ouellette, M, and Tiller, DK. 1990. The Effects of Luminous Surroundings on Visual Performance, Pupil Size and Human Preference, *J. of the IES*, 19(no. 2).

Table 1. Probability of Seeing Analysis

A:

Natural Pupil

	Scotopically Rich (F213)	Scotopically Deficient (Pink)	Difference
Corrected	10.0 (9.9, 11)	12.5 (11.3, 13.7)	-2.5 (-1.9, -3.3) $p < 0.0025$
+0.50 DS Blur	16.5 (15, 17.2)	23.7 (20.6, 27.2)	-7.2 (-5.4, -9.0) $p < 0.0006$
Difference	-6.2 (-5.2, -7.2) $p < 0.0001$	-10.9 (-9.2, -12.4) $p < 0.0001$	

Surround by Blur Interaction $p<0.19$

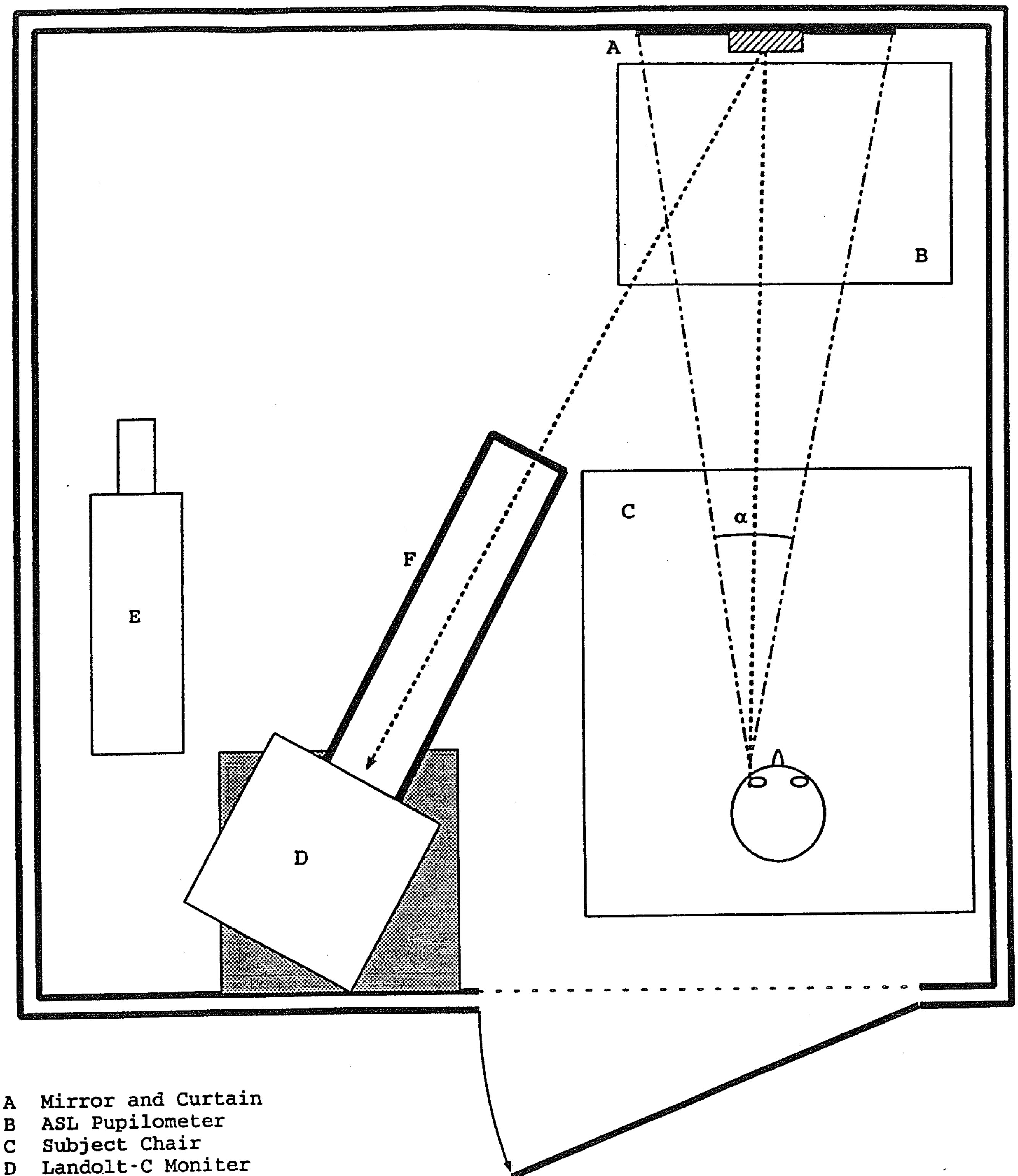
B:

Dilated Pupil

	Scotopically Rich (F213)	Scotopically Deficient (Pink)	Difference
Corrected	17.5 (15.7, 19.4)	16.8 (15.1, 19.8)	0.7 (-0.6, 1.9) $p < 0.6183$
+0.50 DS Blur	30.7 (27, 34.7)	28.2 (25.1, 31.8)	2.5 (1.0, 3.8) $p < 0.1207$
Difference	-12.8 (-10.4, -15.3) $p < 0.0001$	-11.4 (-9.3, -13.7) $p < 0.0001$	

Surround by Blur Interaction $p<0.55$

Individual cell values are mean threshold contrast, i.e. the value at 50 percent probability-of-seeing. Parenthetical values indicate the contrast interval containing 1 s.e., in percent. Standard error intervals are not symmetrical due to the transformation from log to linear units.



A Mirror and Curtain
B ASL Pupilometer
C Subject Chair
D Landolt-C Moniter
E Pritchard 1980B
F Matte Black Baffle Tube
α 20 degrees

Figure 1: Location of the equipment used. The task luminance was kept independent from the surround luminance by means of the velvet curtain (D) and black tube (B), which together subtended approximately 20 degrees both horizontally and vertically.

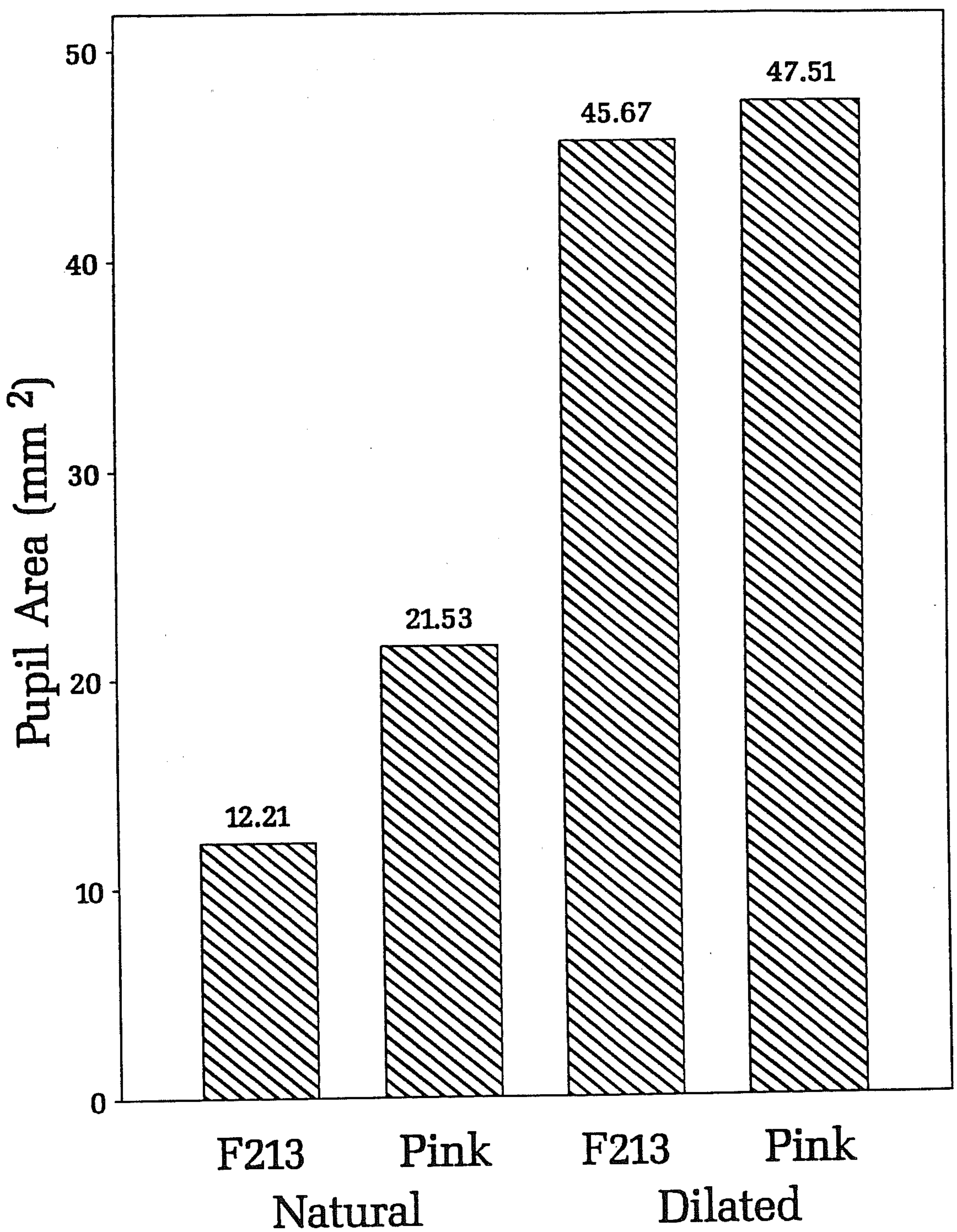


Figure 2: Mean pupil area across 12 subjects for each of the eight conditions.

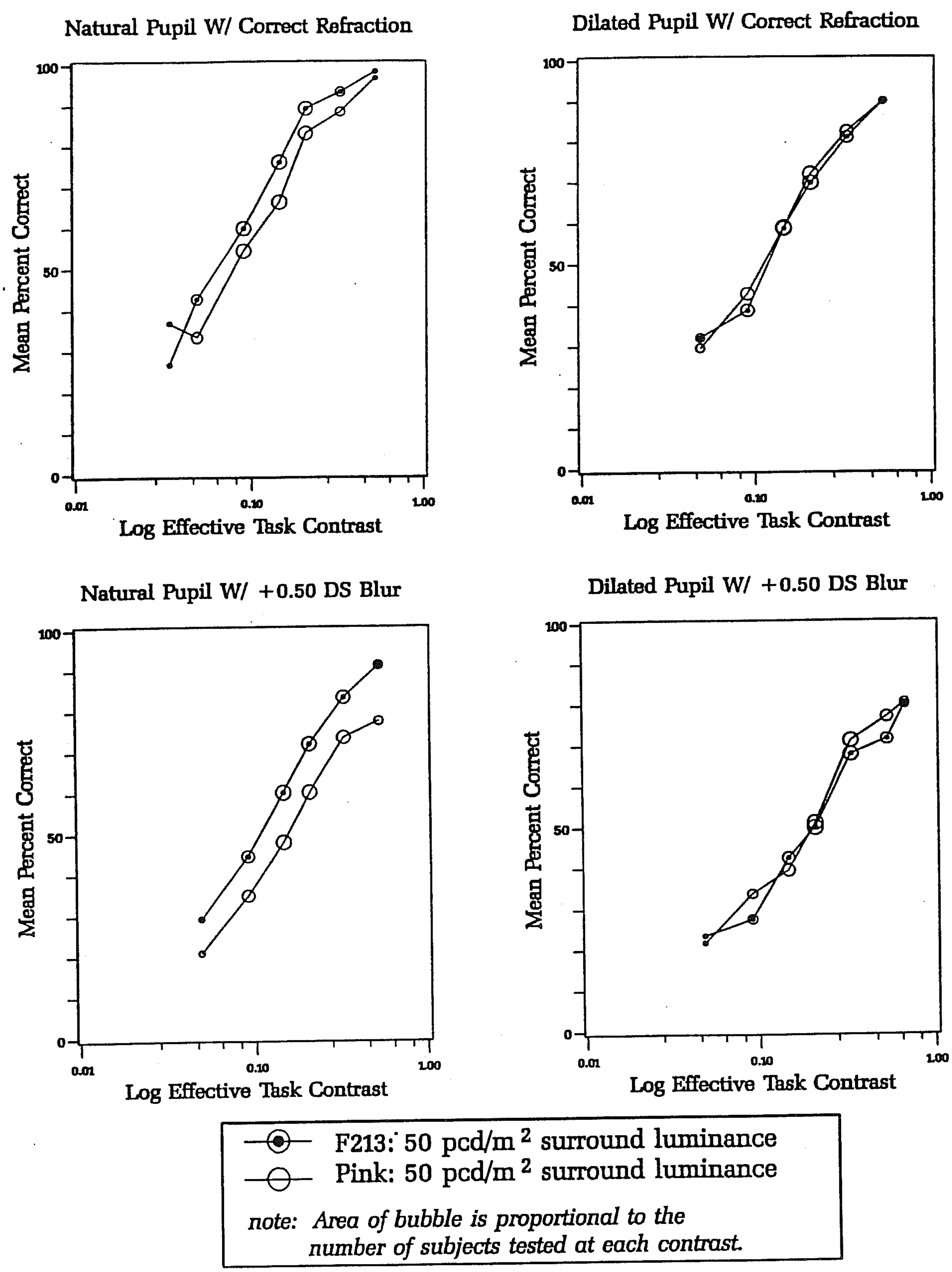


Figure 3: Mean percent correct for recognition of orientation of a Landolt C as a function of its contrast (light background, 13.3 cd/m^2, and dark C) for natural and dilated pupils with and without a +0.50 DS blur lens. F213 and Pink are the scotopically enhanced and scotopically deficient surround illuminants, respectively.